Aruba: A re-evaluation of petroleum prospectivity following the recent discoveries in the Gulf of Venezuela

Following the only offshore wells drilled back-to-back in 1989/1990, whose primary targets turned out to be non-reservoir, Alan Holden* makes the case for a fresh look at an area that has seen no active exploration since 1990.

The island of Aruba is located to the north of South America, approximately 27 km at its closest point from the Venezuelan coast (Figure 1). Aruba lies on crust that once probably formed part of the island arc of the Caribbean Plate and which has now, in part, been obducted onto the northern margin of South America. Seismic data was acquired offshore Aruba in 1979/1980 and in 1989, with the latter's acquisition associated with the only drilling campaign during which three wells were drilled back-to-back in 1989 and 1990. There has been no active exploration since 1990. The recent discovery wells immediately to the south in the Gulf of Venezuela have re-ignited interest in this overlooked area.

Tectonic framework

Understanding the tectonic history of the Caribbean Plate and its relationship with the north of the South American Plate is crucial in understanding the petroleum systems, plays, and prospectivity of offshore Aruba. The Caribbean Plate, moving west to east in an overall compressive setting, was progressively obducted west to east along the northern margin of the continental South American Plate from Paleocene to Middle Miocene times. As a result of the obduction and right-lateral transtension, a number of basins developed including the Falcon Basin, Gulf of Venezuela Basin, and two basins around Aruba, one to the west/southwest and another to the east/southeast. From the end of the Middle Miocene movement of the Caribbean Plate relative to the South American Plate changed from southeast to east, resulting in the dextral strike-slip regime seen today. This change at the end of the Middle Miocene resulted in the uplift of a number of areas including the Falcon Basin and changes in subsidence and sedimentation patterns, including offshore Aruba.

Neighbouring hydrocarbon discoveries

The Falcon Basin has been an area of oil exploration since the early part of the 20th Century, with the discoveries of the Cumarebo and La Vela Fields in 1928/1929. Oil and gas are reservoired in Lower Miocene carbonates and Oligocene and Lower–Middle Miocene sandstones. La Vela Field was also reported to have tested hydrocarbons from fractured basement (Occidental of Aruba, 1990; Payne, 1951;

Figure 1 Detailed location map.

* *Fugro Robertson, Llandudno, LL30 1SA, North Wales, UK. E-mail: alan.holden@fugro-robertson.com*

Wheeler, 1963). These reservoirs have a similar depositional setting to parts of offshore Aruba.

West of the Guajira peninsula, significant volumes of recoverable gas (7 tcf) are reservoired in Lower Miocene sandstones and carbonate mounds, and Oligocene sandstones in Chuchupa and Ballena Fields, with further reserves in Riohacha Field. Neighbouring wells, Aruchara-1 and Epehin-1, tested gas (up to 11 mmcfgd) from Upper–Middle Miocene sands (Castilletes Formation) and Santa Ana-1 is reported to have 400 bcf gas initially in place (GIIP) (Ramirez, 2006).

Five exploration wells, Tuna-1X, Perla-1X, Perla-2X, and two in Urumaco I Block, have recently been drilled in the Gulf of Venezuela. There is little information regarding the result of Tuna-1X, drilled by Chevron in Cardon III Block lying immediately to the south of Aruban waters. Perla-1X, drilled by Repsol in Cardon IV Block, was reported to be a major gas discovery and, following the drilling of Perla-2X, recoverable gas reserves have been placed at 9-10.5 tcf. During testing, Perla-1X flowed at 0.57 million cmgd, plus 620 bcpd. Perla-2X encountered 840 ft net pay and a production test flowed 1.4 million cmgd and 1500 bcpd (Repsol, 2009 and 2010) (Figure 2).

Petroleum systems

Regional thermogenic source rocks

Potential thermogenic source rocks along northern South America are of Jurassic, Cretaceous, and Tertiary age. Two time intervals are the most important: the Cenomanian–Campanian, and the Miocene–Pliocene, while there are contributions from the Jurassic–Lower Cretaceous, Paleocene–Lower Eocene and Oligocene. Onshore Venezuela, the main thermogenic source rock is the Cretaceous La Luna Formation and its equivalents, although Tertiary thermogenic source rocks are important locally. In most of the offshore, including Aruba, the thermogenic petroleum systems are Tertiary, the only exception being offshore central and southern Trinidad where the Cretaceous is dominant. The different distributions of the two petroleum systems relate to a tectonic/thermal event which effectively destroyed Cretaceous thermogenic source rocks on the southern margin of the Caribbean Plate at the end of the Cretaceous/start of the Tertiary (Curet, 1992). The Tertiary is therefore the potential thermogenic petroleum system offshore Aruba.

Tertiary thermogenic source rocks

In the Cariaco Basin, Eocene, Oligocene, and Miocene marine shales have been suggested as potential source rocks and may be the charge for discoveries in the basin. Gorney et al. (2007) suggest that the Mamon Field, adjacent to the Urumaco Trough, and the La Vela and Cumarebo Fields in the Falcon Basin, are charged from the Oligocene and Miocene Agua Clara and Cerro Pelado Formations, with the Eocene Guarabal Formation also being suggested as a source in the La Vela Bay area. Condensate in the Rio Caribe Field in the Carupano Basin also suggests a Tertiary thermogenic petroleum system is active (James, 2000) (Figure 1).

Tertiary biogenic source rocks

Commercial gas discoveries with a biogenic source are found in the Columbus and Carupano Basins and adjacent to the Guajira Peninsula. In the Guajira Peninsula area, Katz and Williams (2003) suggest that the gas in the Ballena, Riohacha, and Chuchupa Fields is most likely to be biogenic in origin. These findings are confirmed by Rangel et al. (2003) but they also suggest the gas in Chuchupa Field is mixed biogenic-thermogenic.

Source rocks offshore Aruba

Total organic carbon (TOC) analyses of ditch cuttings from the three wells offshore Aruba average approximately 1 wt. % and ranges up to 2.64 wt %. S2 ranges up to 2.91 mgHC/g rock and HI up to 253 mgHC/gTOC. All well sections were either immature or just into the early oil window at the base of the well. Seismic suggests the wells drilled offshore Aruba only penetrated the upper part of the sedimentary section, indicating that narrow, thick depocentres either side of Aruba were not penetrated. These narrow, thick, deep basins could have been areas of restricted marine circulation where thermogenic source rocks developed.

The occurrence of significant amounts of biogenic gas along the north of South America relates to the low geothermal gradient and significant recent sedimentation containing organic matter, which allows biogenic gas to be generated from a significant volume of sediment. These conditions are present offshore Aruba. The geothermal gradient, calculated from corrected bottom hole temperatures from the three wells offshore Aruba, is approximately 18–20°C/km.

Exploration history

Seismic acquisition

From 1975 to 1977 a group shoot, SEAGAP, acquired regional 2D seismic data from Nicaragua to Guyana, including the area to the north of Aruba. In 1977/1978 Western also acquired a dense 2D seismic survey to the west/southwest of Aruba. Three further 2D surveys were acquired in 1989 to the west/southwest of Aruba for a drilling campaign during 1989/1990. The SEAGAP and the majority of the 1989 data have been reprocessed by Fugro Robertson (GeoSpec).

Well history and details

Three wells, Divi Divi-1, Mero-1X, and Chuchubi-1, have been drilled offshore Aruba. The wells, drilled in 1989/1990, are all located to the west/southwest of Aruba and none discovered commercial hydrocarbons; however, there are indicators for the presence of gas and condensate in the well data.

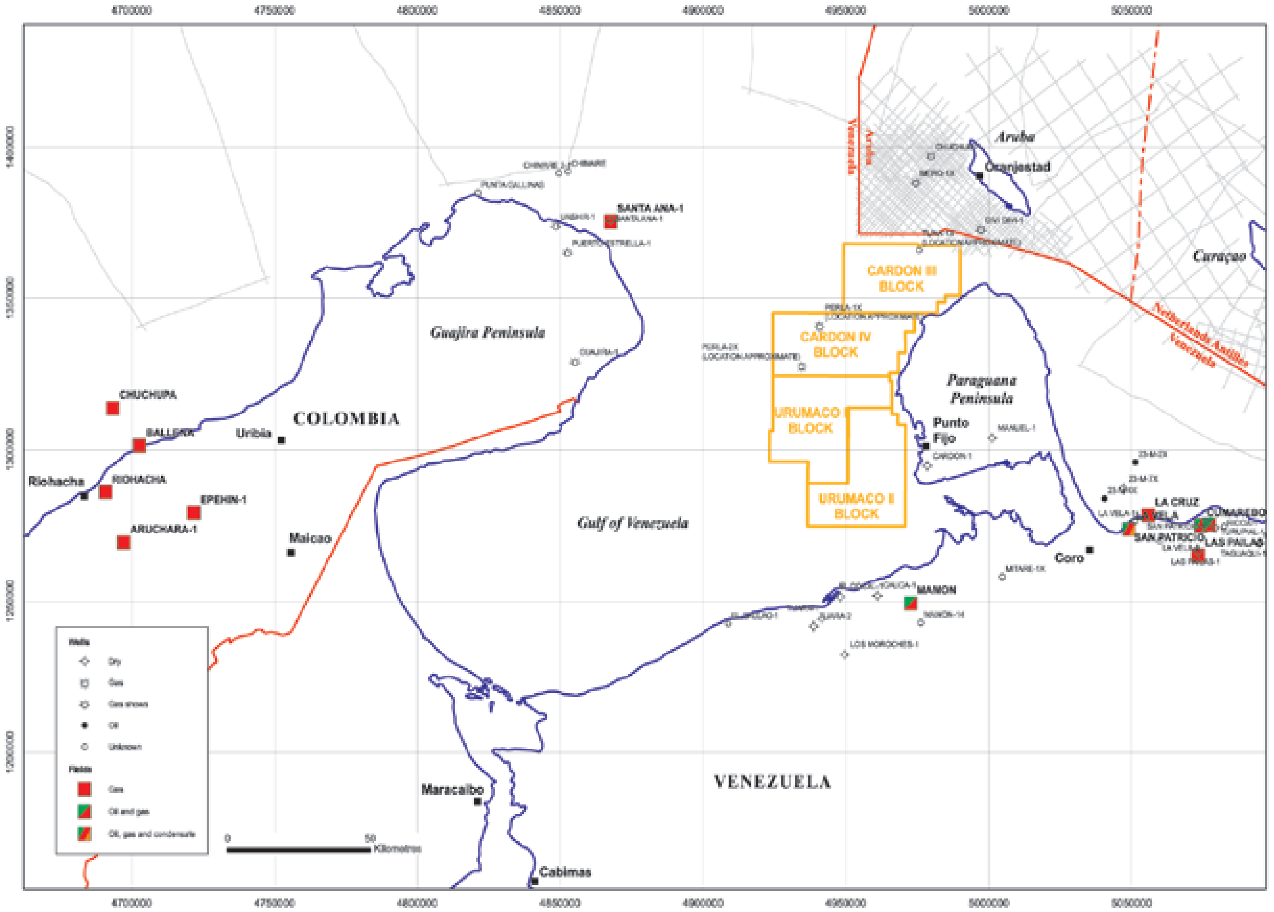

Figure 2 Oil and gas discoveries around offshore Aruba.

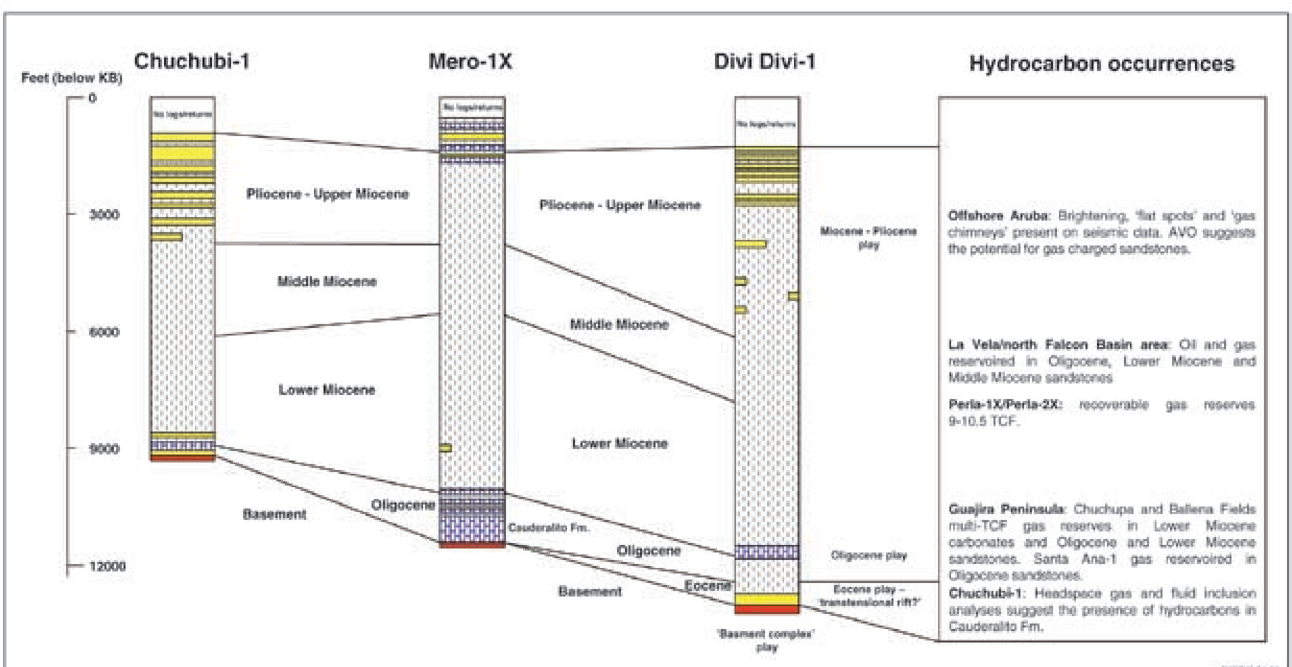

Figure 3 Well correlation and hydrocarbon occurrences.

Mero-1X and Chuchubi-1 both TD in igneous basement, but the TD for Divi Divi-1 is reached in an 'Eocene basement complex' consisting of conglomerate. Overlying the 'Eocene basement complex' are Eocene quartz sandstones. In Mero-1X and Chuchubi-1, the basement is overlain by Oligocene sediments. The Oligocene to Recent sedimentary section consists of carbonates, sandstones, and mudstones (Curet, 1992) (Figure 3).

The primary target of all the wells was the Oligocene – basal Miocene limestones of the Cauderalito Formation within structural traps, locally with a stratigraphic component; however, the Cauderalito Formation in the wells was represented by a micritic non-reservoir facies. Locally, lack of charge and absence of closure may have contributed to the failure.

Outcrop and onshore data

Outcrop data on Aruba, Curacao, and Bonaire can aid the interpretation of the sedimentary section offshore Aruba. A 400 m thick Eocene (and possibly Upper Paleocene) fluviatile conglomerate (Beets et al. 1977), the Soebi Blanco Formation, occurs on Bonaire. It contains a large number of exotic pebbles in addition to those derived from the Washikemba Formation which forms the volcanic core of the island. Most of the exotics are leucocratic gneisses and granulitic rocks, with minor amounts of quartzites, schists, and amphibolites (Figure 4). None of these rocks occur on the island chain of the Netherlands and Venezuelan Antilles. U-Pb analysis of zircon fractions from a granulitic pebble by Priem et al. (1986) suggests the pebble was derived from Precambrian basement with an age of approximately 1150 Ma. Priem et al. (1986) suggest that the source was the Guajira Peninsula, now some 300 km to the west. The conglomeratic nature of the beds suggests that at the time of deposition, Bonaire was close to the Guajira Peninsula and tectonics have since moved Bonaire to its present position.

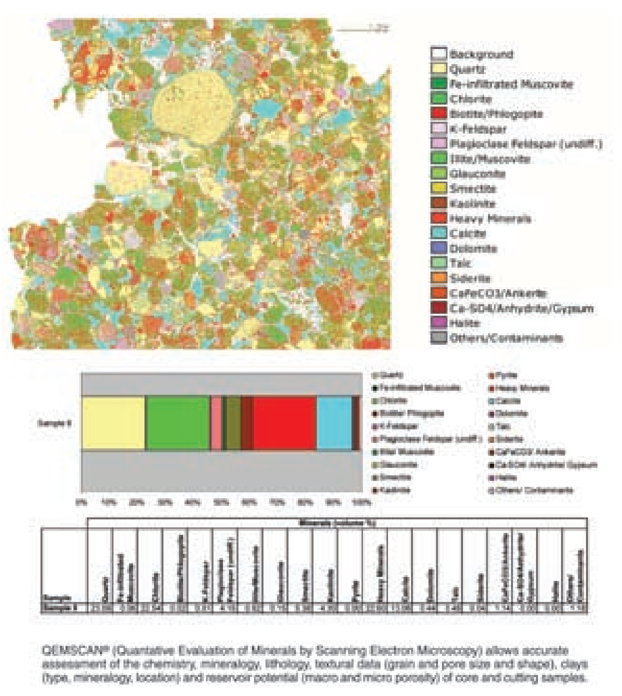

***Figure 4** QEMSCAN® analysis: Soebi Blanco Formation, Bonaire.*

A basal conglomerate of Eocene age also occurs on Curaçao (MacGillavry, 1977). Marls/sandy marls of possible Eocene age occur on Curaçao; significant reworking of Maastrichtian nannofossils is recorded in samples analyzed from this outcrop, suggesting unmetamorphosed Maastrichtian sediments must have been eroded nearby. This indicates that not all the Cretaceous was affected by the thermal event at the end of the Cretaceous/start of the Tertiary.

Three detrital coral species indicative of the 'Mid Oligocene Antigua coral fauna' have been found in phosphate deposits in the southeast of Aruba (Stienstra, 1991) indicating that shallow water Cauderalito Formation equivalent limestones are present around Aruba. Lower and Middle Miocene sands were reported by Westermann (1951) from a water borehole drilled in Oranjestand, Aruba, from 1942–1943. De Buisonjé (1974) suggests that these sands may correlate with the phosphatic sandstones on the northeast of Aruba.

Hydrocarbon indicators offshore Aruba

High levels of C1 gas are recorded in the Divi Divi-1 well above about 10,000 ft with peaks of up to 7% and 4.7% in Mero-1X and Chuchubi-1, respectively. Headspace gas analysis in Chuchubi-1 suggests the presence of condensate (Curet, 1992) in the target reservoir section, the Cauderalito Formation, at the base of the well. Fluid inclusion analysis over this interval also indicates the presence of hydrocarbons.

Indirect evidence for the occurrence of hydrocarbons comes from gas chimneys present over a structural high to the northwest of Aruba, satellite seep data from Fugro NPA which in adjacent areas indicate potential active seepage and from 'flat spots' observed on seismic data and also attribute analysis of the seismic. Following reprocessing and velocity studies, a series of AVO attribute analysis tests were run on selected lines in order to assess the presence and extent of AVO anomalies and other DHIs. These tests, which included intercept vs gradient crossplots, confirmed that AVO anomalies did exist in the data.

Basin geometry and sedimentary fill offshore Aruba

Two basins are present offshore Aruba (Figure 5). A shallow water basin is present to the west/southwest with a deepwater basin to the east/southeast which extends further to the southeast to the south of Curaçao. Both basins have a northwest to southeast orientation and developed initially probably during the Eocene. The basin to the west/southwest

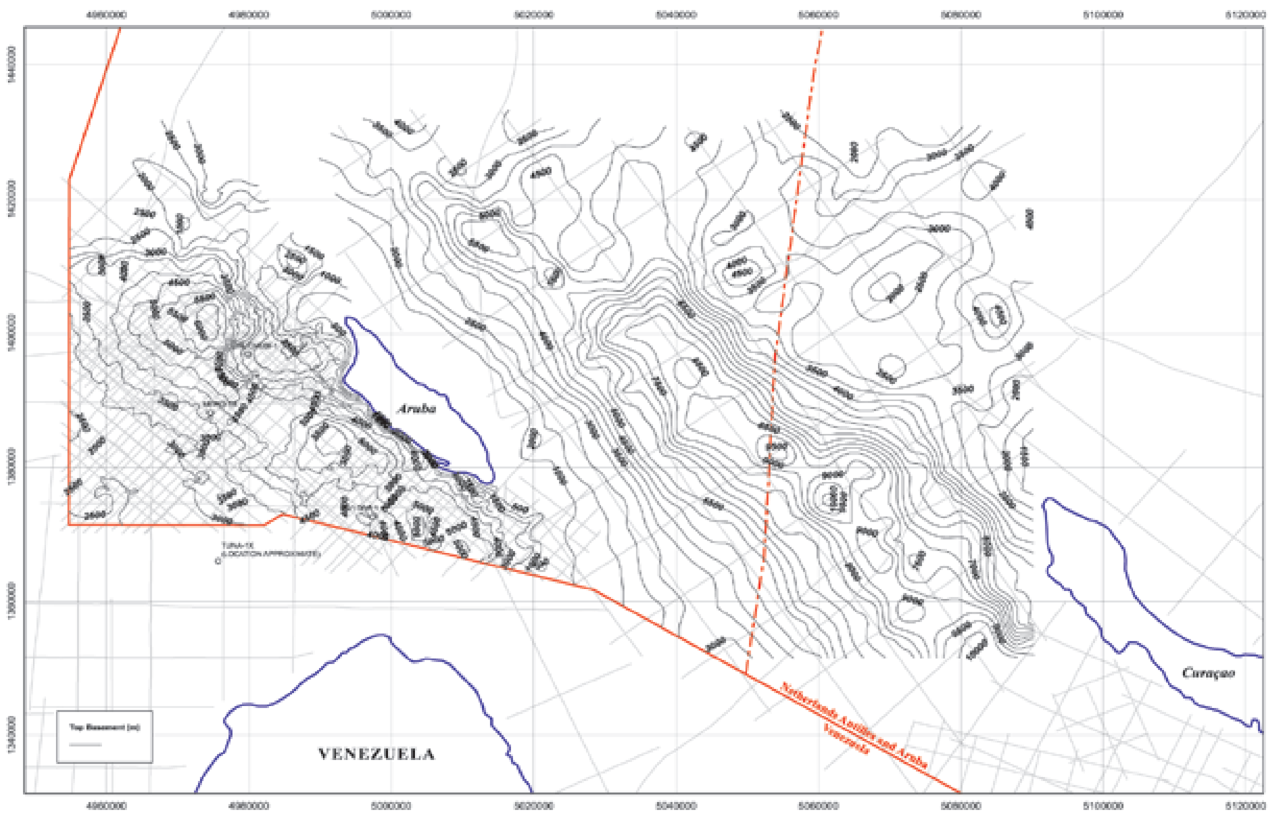

Figure 5 *Depth structure map – top Igneous Basement.*

contains the three wells drilled in 1989/1990. The basin to the east/southeast is undrilled.

Well and seismic data allow the sedimentary fill of the basin to the west/southwest to be divided into four units (Figure 6) as follows:

'Eocene unit'

This is the deepest unit, whose base on seismic can be below 5 seconds TWT and exceeds 6 km depth. The top of the unit has been penetrated by well Divi Divi-1 where it is composed of Eocene sandstones, these being a lateral equivalent of the conglomerates of similar age seen on Bonaire and Curaçao. Areas of thick 'Eocene unit' are restricted to the main depocentres, probably being deposited during the initial transtensional development of the basin; however, as this interval is preserved on Bonaire and Curaçao, a thinner succession may be preserved outside the basin centres and represents a potential exploration target. Proprietary QEMSCAN analysis of the Eocene sandstone in Divi Divi-1 indicates it is quartz rich and together with the conglomerate on Bonaire suggests derivation from the South American continental crust. The 'Eocene unit' on seismic is marked by variably continuous reflectors which become locally chaotic, and show variable amplitude. The unit onlaps the basin margins markedly.

'Oligocene unit'

Over the 'Eocene unit' lies a thinner unit of shales which are capped by the Cauderalito Formation limestones. On seismic, this 'Oligocene unit' is characterized by broad parallel reflectors with strong amplitudes at the top, marking the upward change from the Cauderalito Formation limestones into the overlying mudstones of the 'Base Miocene unit'. The unit onlaps the basin margins and possibly drapes over structural highs. The top of the interval can be greater than 4 seconds TWT or less than 2.5 seconds TWT, this change in part representing the original water depth of deepwater micritic deposition in the basin centre to shallow water Cauderalito Formation limestones on the basin margins.

'Base Miocene unit'

Marked by sub-parallel reflectors and represented in the wells by a dominantly mud prone sequence with indications of sandstone, the 'Base Miocene Unit' strongly onlaps the basin margin and structural highs.

'Top Miocene – Recent unit'

Marked by a basal chaotic unit, the 'Top Miocene – Recent Unit' exhibits stronger amplitudes and is strongly downlapping, prograding from the southwest/south. Deposition of

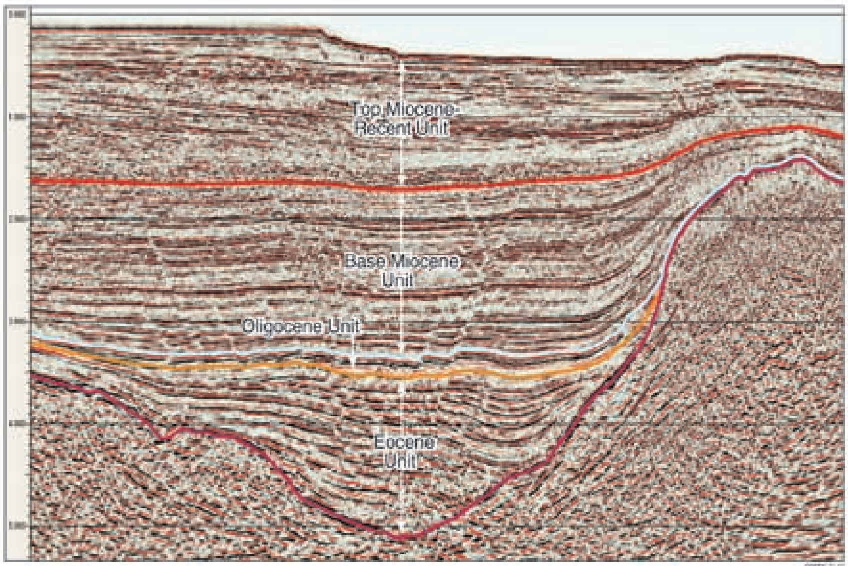

***Figure 6** Depositional/seismic units in the basin to the west/southwest of Aruba.*

this unit probably relates to the switch in plate movement to the current dextral strike-slip regime and resultant uplift to the south.

The basin to the east/southeast of Aruba is undrilled and is separated from the basin to the west/southwest by the structural high which forms the island of Aruba. This makes it difficult to tie the seismic data between the two basins; however, the fill of the basins using the character of the seismic appears to be similar.

Potential reservoirs/plays offshore Aruba

Basement

Mero-1X and Chuchubi-1 penetrated this interval, with Divi Divi-1 TD being in a 'basement complex', where drilling mud losses indicate the interval is fractured or has traditional reservoir potential. Seismic suggests faulting has taken place up to recent times, potentially developing fractured reservoirs along such zones.

Outcrop on Aruba is dominated by a quartz diorite/tonalite intrusion. QEMSCAN analysis of the 'basement complex' in Divi Divi-1 indicates intermediate basement. Erosion of these quartz diorites may be an additional local source of coarse clastic sediments rather than sediment deriving from South America. This play has potential in faulted structural traps and 'palaeo' highs.

Geochemical modelling suggests the basin centre to the east/southeast of Aruba has reached condensate maturity, with a significant area within the peak oil window. The basin to the west/southwest was also modelled to have reached condensate maturity in the basin centre, with areas of peak oil being more restricted than those in the basin to the east/southeast. A thermogenic charge, if source rocks are present in depocentres, is possible to all plays, particularly in areas of faulting, on the basin flanks, or in areas with thinner Miocene shale. A biogenic charge could occur in any structurally elevated trap.

Eocene

Only Divi Divi-1 has penetrated the 'Eocene unit' which consists of fine to medium, occasionally to very coarse grained sandstone with subrounded to rounded grains, and along with the derivation information from the conglomerate of similar age on Bonaire, suggests significant transport, probably from the South American Plate. Petrophysical analysis in Divi Divi-1 indicates an average porosity of 15%. Reservoir sandstones could be widespread in this interval, both in depocentres and in thinner preserved intervals on basin flanks.

Undrilled structural traps are present in the west/southwest basin but stratigraphic traps on the flanks are also possible targets. Structural traps should be present in the basin to the east/southeast of Aruba but the current 10 km wide seismic grid makes it impossible to map them out.

Oligocene

Carbonates of probable Oligocene age deposited in shallow water are present on Aruba (Stienstra, 1991) and undrilled structures with potential shallow water carbonate reservoirs have been mapped offshore Aruba. These structures are potentially analogous to the discoveries in the Gulf of Venezuela. Sandstones are also interbedded with the Caudericalito Formation limestones in Chuchubi-1, suggesting clastic reservoirs are also developed.

Miocene – Pliocene

In the three wells offshore Aruba, sands were recorded in the Upper Miocene – Pliocene interval. The changes in seismic character over this interval suggest changes in lithology. Given the relatively shallow burial, reservoir quality in clean sands should be good. 'Flat spots' are present in this interval. Traps are likely to be a combination of structural and stratigraphic. Large structures can be mapped from the seismic in the basin to the east/southeast.

Conclusions

There are two potential source rock intervals offshore Aruba. The oldest, an oil prone thermogenic source, would be Eocene in age and restricted to the deeper parts of the offshore area, where marine restriction is assumed to have occurred during initial basin development resulting in source rock deposition. The second potential source is biogenic in origin, producing a possible gas charge. There is evidence for both a thermogenic and biogenic petroleum system offshore Aruba.

Possible reservoir rocks are present in the basement and in the overlying sedimentary section of Eocene to Recent age. Potential can be seen in structural and stratigraphic traps.

With the recent major discoveries reported in the Gulf of Venezuela, neighbouring offshore Aruba has already generated renewed industry interest and, with its similar geological characteristics and hydrocarbon indicators, certainly warrants a re-examination by the industry with regards to its potential.

Acknowledgements

This work would not have been possible without the kind assistance and guidance of Armando Curet of Compania Arubano di Petroleo, from whom further information regarding the exploration opportunities of Aruba can be obtained.

References

Beets, D.J., Macgillavry, H.J. and Klaver, G.T. [1977] Geology and the Cretaceous and Early Tertiary of Bonaire. In: Guide to geological excursions on Curaçao, Bonaire and Aruba. *Stinapa Publication*, **15**.

Curet, E.A. [1992] Stratigraphy and evolution of the Tertiary Aruba Basin. *Journal of Petroleum Geology*, **15**(3), 283-304.

De Buisonje, P.H. [1974] *Neogene and Quaternary geology of Aruba, Curaçao and Bonaire*. Uitgaven Natuurwetenschappelijke studiekring voor Suriname en de Nederlandse Antillen, pp. 293.

Gorney, D., Escalona, A., Mann, P., Magnani, M.B. and Bolivar Study Group [2007] Chronology of Cenozoic tectonic events in western Venezuela and the Leeward Antilles based on integration of offshore seismic reflection data and on-land geology. *AAPG*, **91**, 653–684.

James, K.H. [2000] The Venezuelan hydrocarbon habitat, Part 1: tectonics, structure, palaeogeography and source rocks. *Journal of Petroleum Geology*, **23**(1), 5–53.

Katz, B. and Williams, K. [2003] Biogenic gas potential offshore Guajira Peninsula, Colombia. In: Bartolini, C., Buffler, R.T. and Blickwede, J. (Eds) The Circum-Gulf of Mexico and the Caribbean: hydrocarbon habitats, basin formation and plate tectonics. *AAPG Memoir*,**79**, 961–968.

Macgillavry, H.J. [1977] Tertiary formations. In: Eighth Caribbean Geological Conference Guide to the Field Excursions on Curaçao, Bonaire and Aruba. *GUA Papers of Geology*, **10**, 36–38.

Occidental of Aruba [1990] Chuchubi-1 final well report, **1**, 125.

Payne, A.L. [1951] Cumarebo oil field, Falcon, Venezuela. *AAPG Bulletin*, **35**(8), 1850-1878.

Priem, H.N.A., Beets, D.J. and Verdurmen, E.A.Th. [1986] Precambrian rocks in an Early Tertiary conglomerate on Bonaire, Netherlands Antilles (southern Caribbean borderland): evidence for a 300 km eastward displacement relative to the South American mainland? *Geologie en Mijnbouw*, **65**, 350–40.

Ramirez, V. [2006] Setting and hydrocarbon Guajira Basin, offshore northern Colombia. *AAPG Annual Convention* (poster).

Rangel, A., Katz, B., Ramirez, V. and Vaz Dos Santos Neto, E. [2003] Alternative interpretations as to the origin of the hydrocarbons of the Guajira Basin, Colombia. *Marine and Petroleum Geology*, **20**, 129–139.

Repsol [2009] Repsol confirms Venezuela's Perla-1X well as its largest ever gas find. *Press release*. 16 October 2009.

Repsol [2010] Repsol increases by at least 30% its reserves estimate in the Perla Field. *Press release* 12 April 2010.

Stienstra, P. [1991] *Sedimentary petrology, origin and mining history of the phosphate rocks of Klein Curaçao, Curaçao and Aruba, Netherlands West Indies*. Natuurwetenschappelijke Studiekring voor het Caribische gebied, pp. 130.

Westermann, J.H. [1951] The waterbore of Oranjestad – 1942–43 and its implications as to the geology and geohydrology of the island of Aruba. *Proceedings of the Koninklijke Nederlandse Akademie van Wetenschappen*, **B54**(2), 140–159.

Wheeler, C.B. [1963] Oligocene and Lower Miocene stratigraphy of western and northeastern Falcon Basin, Venezuela. *AAPG Bulletin*, **47**(1), 35–68.